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VOLUME II

A THREE-DIMENSIONAL INVISCID BLUNT BODY CODE
FOR ASYMMETRIC NOSETIPS IN PITCH AND YAW

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This report documents modifications made to the Moretti inviscid three-dimensional blunt body code to remove the assumption of a pitch plane of symmetry. Details are provided on the analysis required to extend this code to treat fully asymmetric nosetip geometries at both angle of attack (α) and sideslip (β). Modifications to the code inputs required for this capability are also described.

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SECTION 1

INTRODUCTION

This report documents modifications made to the three-dimensional inviscid Moretti blunt body flow field code to remove the assumption of a pitch plane of symmetry. These modifications make possible calculations at sideslip (β) as well as angle of attack (α), and also allow calculations to be made on asymmetric nosetip geometries that do not have a pitch plane of symmetry.

The blunt body code being modified is based on the analysis of Moretti[1], and was first documented by Kyriss and Harris[2]. A more detailed exposition of this original analysis is given in Reference 3. The ability of the Moretti blunt body code to accurately compute inviscid flows over ablated nosetip geometries (subject to the restrictions of the assumption of a pitch plane of symmetry) has been investigated and demonstrated by Hall, Kyriss, Truncellito and Martellucci[4].

The Moretti blunt body code is based upon an inviscid, time-dependent technique which solves the governing equations in non-conservation form using the second-order accurate MacCormack[5] finite difference scheme. The equations are formulated in a spherical-polar coordinate system, and either ideal or equilibrium air thermodynamics may be used in the calculations.

Special forms of the governing equations are required along the singular centerline of the spherical-polar coordinate system. In the original form of this blunt body code, these special forms were derived under the assumption of a pitch plane of symmetry, in which many of the terms in the pitch plane vanish.

As part of the current effort to remove the pitch plane of symmetry assumption, special limiting forms of the governing equations have been developed to allow treatment of non-symmetric geometries and sideslip. The new centerline equations are presented in Section 2.1 of this report. The treatment of sideslip at shock points is discussed in Section 2.2, and the finite difference expressions required by the new centerline equations are described in Section 2.3. Changes made to the body geometry specification procedure are given in Section 2.4. Finally, changes in the code inputs required by this modification effort are given in Section 2.5.

SECTION 2

ANALYSIS

2.1 Governing Equations at Centerline

In the (r,θ,ϕ) spherical-polar coordinate system, shown in Figure 1, the governing inviscid equations may be written as:

$$P_t + uP_r + vP_\theta/r + wP_\phi/r \sin\theta + \gamma(u_r + v_\theta/r + w_\phi/r \sin\theta + 2u/r + v \cot\theta/r) = 0 \qquad (1)$$

$$u_t + uu_r + vu_\theta/r + wu_\phi/r \sin\theta - (v^2 + w^2)/r + pP_r/\rho = 0 \qquad (2)$$

$$v_t + uv_r + vv_\theta/r + wv_\phi/r \sin\theta + uv/r - w^2 \cot\theta/r + pP_\theta/\rho r = 0 \qquad (3)$$

$$w_t + uw_r + vw_\theta/r + ww_\phi/r \sin\theta + uw/r + vw \cot\theta/r + pP_\phi/\rho r \sin\theta = 0 \qquad (4)$$

$$s_t + us_r + vs_\theta/r + ws_\phi/r \sin\theta = 0 \quad , \qquad (5)$$

where P is the logarithm of pressure, u,v, and w are the r,θ, and ϕ velocity components, respectively, and s is the entropy.

At the centerline, where $\theta = \pi$, $\sin\theta = 0$ and $\cot\theta = \infty$, these equations are singular. Removing the singularities results in the following special forms of the equations, valid only along the centerline:

$$P_t + uP_r + vP_\theta/r - wP_{\theta\phi}/r + \gamma(u_r + 2v_\theta/r + 2u/r - w_{\theta\phi}/r) = 0 \tag{6}$$

$$u_t + uu_r + vu_\theta/r - wu_{\theta\phi}/r - (v^2 + w^2)/r + pP_r/\rho = 0 \tag{7}$$

$$v_t + uv_r + vv_\theta/r - wv_{\theta\phi}/r - ww_\theta/r + uv/r + pP_\theta/\rho r = 0 \tag{8}$$

$$w_t + uw_r + vw_\theta/r - ww_{\theta\phi}/r + wv_\theta/r + uw/r - pP_{\theta\phi}/\rho r = 0 \tag{9}$$

$$s_t + us_r + vs_\theta/r - ws_{\theta\phi}/r = 0 \quad . \tag{10}$$

In the previous analysis, with the assumption of a pitch plane of symmetry, these equations are used only in the plane of symmetry, where $w = 0$, $w_\theta = w_r = 0$, and $P_{\theta\phi} = s_{\theta\phi} = u_{\theta\phi} = v_{\theta\phi} = 0$, thus simplifying the analysis.

The generalized equations valid at the centerline, Equations (6) - (10), are transformed to the computational space using the transformation defined by:

$$Z = [r - r_b(\theta,\phi)]/[r_s(\theta,\phi,t) - r_b(\theta,\phi)] \tag{11}$$

$$Y = \pi - \theta \tag{12}$$

$$X = \phi \tag{13}$$

where the body surface is defined by $r = r_b(\theta,\phi)$ and the bow shock surface by $r = r_s(\theta,\phi,t)$. Derivatives are transformed according to the chain rule, resulting in

$$\frac{\partial}{\partial r} = \frac{1}{\delta}\frac{\partial}{\partial Z} \tag{14}$$

$$\frac{\partial}{\partial \theta} = -\frac{\partial}{\partial Y} + \frac{1}{\delta}\left[(Z-1)r_{b_\theta} - Zr_{s_\theta}\right]\frac{\partial}{\partial Z} \tag{15}$$

$$\frac{\partial}{\partial \phi} = \frac{\partial}{\partial X} + \frac{1}{\delta}\left[(Z-1)r_{b_\phi} - Zr_{s_\phi}\right]\frac{\partial}{\partial Z} \tag{16}$$

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial T} - \frac{Zr_{st}}{\delta}\frac{\partial}{\partial Z} \tag{17}$$

where $\delta = r_s(\theta,\phi,t) - r_b(\theta,\phi)$.

Also, at the centerline:

$$\begin{aligned}\frac{\partial^2}{\partial\theta\partial\phi} = &-\frac{\partial^2}{\partial X\partial Y} + \frac{1}{\delta}\left[(Z-1)r_{b_{\theta\phi}} - Zr_{s_{\theta\phi}}\right]\frac{\partial}{\partial Z}\\ &+ \frac{1}{\delta}\left[(Z-1)r_{b_\theta} - Zr_{s_\theta}\right]\frac{\partial^2}{\partial X\partial Z} .\end{aligned} \tag{18}$$

Following the coordinate transformation, the governing equations, both on and off the centerline, may be written in one form, where certain coefficients take different values at the centerline from their values elsewhere. The resulting general forms of the equations may be written as

$$\begin{aligned}P_T + AP_Y + NP_X + FP_Z + M_1 + \gamma[u_Z/\delta + Bv_Z\\ + Ew_X + Jw_Z + W + (2u - v_Y)/r + H] = 0\end{aligned} \tag{19}$$

$$u_T + Au_Y + Nu_X + Fu_Z + M_2 - (v^2 + w^2)/r$$
$$+ pP_Z/\delta\rho = 0 \tag{20}$$

$$v_T + Av_Y + Nv_X + Fv_Z + M_3 - Au - K$$
$$+ p(BP_Z - P_Y/r)/\rho = 0 \tag{21}$$

$$w_T + Aw_Y + Nw_X + Fw_Z + M_4 + uw/r + L$$
$$+ p(EP_X + JP_Z + \bar{P})/\rho = 0 \tag{22}$$

$$s_T + As_Y + Ns_X + Fs_Z + M_5 = 0 \quad . \tag{23}$$

Coefficients whose expressions are the same both on and off the centerline are

$$C = (Z-1)r_{b_\theta} - Zr_{s_\theta}$$

$$Q = (Z-1)r_{b_\phi} - Zr_{s_\phi}$$

$$A = -v/r$$

$$B = C/r\delta$$

$$N = Ew$$

$$F = (u - Zr_{s_t} - AC + NQ)/\delta$$

$$J = EQ/\delta \quad .$$

At points off the centerline, the remaining coefficients take the forms

$$E = 1/r \sin \theta$$

$$H = Ev \cos \theta$$

$$K = Nw \cos \theta$$

$$L = wH$$

$$\overline{P} = 0$$

$$W = 0$$

$$M_1 = M_2 = M_3 = M_4 = M_5 = 0 \quad .$$

On the centerline these coefficients are expressed as

$$E = 0$$

$$H = (-v_Y + Cv_Z/\delta)/r$$

$$K = 2w(-w_Y + Cw_Z/\delta)/r$$

$$L = wH + v(-w_Y + Cw_Z/\delta)/r$$

$$\overline{P} = -(-P_{XY} + CP_{XZ}/\delta + P_Z Q_\theta/\delta)/r$$

$$W = -(-w_{XY} + Cw_{XZ}/\delta + w_Z Q_\theta/\delta)/r$$

$$M_1 = w\overline{P}$$

$$M_2 = -w(-u_{XY} + Cu_{XZ}/\delta + u_Z Q_\theta/\delta)/r$$

$$M_3 = -w(-v_{XY} + Cv_{XZ}/\delta + v_Z Q_\theta/\delta)/r + w(-w_Y + Cw_Z/\delta)/r$$

$$M_4 = wW - v(-w_Y + Cw_Z/\delta)/r$$

$$M_5 = -w(-s_{XY} + Cs_{XZ}/\delta + s_Z Q_\theta/\delta)/r$$

where

$$Q_\theta = Z_\theta(r_{b_\phi} - r_{s_\phi}) + (Z-1) r_{b_{\theta\phi}} - Z r_{s_{\theta\phi}} \quad .$$

Along the centerline, calculations are performed only in the $\phi = 0$ plane. The flow variables P,s, and u at the centerline are the same for all values of ϕ; the v and w velocity components for other values of ϕ may be expressed as

$$v(\phi) = v(0) \cos \phi - w(0) \sin \phi \tag{24}$$

$$w(\phi) = v(0) \sin \phi + w(0) \cos \phi \quad . \tag{25}$$

The equations presented above are used directly at field points on the centerline. At body and shock points, the computational procedures used (which are described in References 2 and 3) require a linear combination of these equations; thus the body and shock point procedures on the centerline require modification to eliminate the plane of symmetry assumption. These modifications follow directly from Equations (19) - (23).

Without a pitch plane of symmetry, however, the expressions for the body and shock normals at the centerline must be modified to allow for components normal to the pitch plane, which previously were zero. The outward body normal at the centerline is now expressed as

$$\hat{n}_b = \frac{\hat{e}_r - r_{b_\theta}/r_b \; \hat{e}_\theta + r_{b_{\theta\phi}}/r_b \; \hat{e}_\phi}{[1 + r_{b_\theta}{}^2/r_b{}^2 + r_{b_{\theta\phi}}{}^2/r_b{}^2]^{1/2}} \tag{26}$$

and the inward shock normal becomes

$$\hat{n}_s = \frac{-\hat{e}_r + r_{s\theta}/r_s \; \hat{e}_\theta - r_{s\theta\phi}/r_s \; \hat{e}_\phi}{[1 + {r_{s\theta}}^2/{r_s}^2 + {r_{s\theta\phi}}^2/{r_s}^2]^{1/2}} \quad . \tag{27}$$

2.2 Treatment of Sideslip

The addition of the capability to handle sideslip ($\beta \neq 0$) requires only that the definition of the freestream velocity vector be altered. Defining the angle of attack (α) and the sideslip angle (β) as shown in Figure 2, the freestream velocity vector may be written in terms of the (r,θ,ϕ) spherical-polar coordinate system as

$$\vec{V}_\infty = u_\infty \hat{e}_r + v_\infty \hat{e}_\theta + w_\infty \hat{e}_\phi \tag{28}$$

where

$$u_\infty = q_\infty[\cos\alpha \cos\beta \cos\theta + (\sin\beta \sin\phi + \sin\alpha \cos\beta \cos\phi)\sin\theta] \tag{29}$$

$$v_\infty = q_\infty[-\cos\alpha \cos\beta \sin\theta + (\sin\beta \sin\phi + \sin\alpha \cos\beta \cos\phi)\cos\theta] \tag{30}$$

$$w_\infty = q_\infty[\sin\beta \cos\phi - \sin\alpha \cos\beta \sin\phi] \tag{31}$$

with $q_\infty = |\vec{V}_\infty|$.

The presence of a non-zero β also effects the definition of the equivalent body angle used to initialize the surface pressures and shock shape. The equivalent body angle is now defined as

$$\theta_{b_{EQ}} = \theta_b - \alpha \cos\phi - \beta \sin\phi \quad , \tag{32}$$

where $$\theta_b = \tan^{-1}\left\{\frac{-(r_{b_\theta}/r_b)\ \sin\theta - \cos\theta}{-(r_{b_\theta}/r_b)\ \cos\theta + \sin\theta}\right\} \quad . \tag{33}$$

2.3 Derivative Approximations

The generalization of the limiting forms of the governing equations at the centerline introduces second derivatives that previously vanished in the pitch plane of symmetry. The finite difference approximations to these derivatives may be written as

$$\frac{\partial^2 f}{\partial X \partial Y} = [f(N,\overline{M} + 1,\ \overline{L} + 1) - f(N,\overline{M},\ \overline{L} + 1)$$
$$-f(N,\overline{M} + 1,\overline{L}) + f(N,\overline{M},\overline{L})]/(\Delta X)(\Delta Y) \tag{34}$$

and

$$\frac{\partial^2 f}{\partial X \partial Z} = [f(\overline{N} + 1,\ M,\overline{L} + 1) - f(\overline{N},\ M,\ \overline{L} + 1)$$
$$-f(\overline{N} + 1,\ M,\overline{L}) + f(\overline{N},M,\overline{L})]/(\Delta X)(\Delta Z) \tag{35}$$

where $Z = N\ \Delta Z$

$Y = M\ \Delta Y$

$X = L\ \Delta X$.

At the centerline the barred indices take the forms

$$\overline{N} = \max[1,\ \min\{N-I + 1,\ NMAX - 1\}] \tag{36}$$

$$\overline{M} = 1 \tag{37}$$

$$\overline{L} = \begin{matrix} 1\ (I = 1) \\ LMAX - 1\ (I = 2) \end{matrix} \tag{38}$$

where I = 1 in the predictor stage and I = 2 in the corrector stage of the MacCormack finite difference scheme. NMAX and LMAX are maximum values of the Z and X indices, respectively. Note that without a pitch plane of symmetry, L = 1 ($\phi = 0°$) and L = LMAX ($\phi = 360°$) correspond to the same physical plane (periodicity condition).

The calculation of $r_{b_{\theta\phi}}$ and $r_{s_{\theta\phi}}$ is performed using Equation (34), noting that (from Equation (18))

$$\frac{\partial^2}{\partial\theta\partial\phi} = -\frac{\partial^2}{\partial X\partial Y} \quad . \tag{39}$$

2.4 Body Geometry

In the original blunt body code, two options exist for the definition of the body geometry, as described in Reference 6. The first geometry option requires the specification of geometric profiles in a number of ϕ planes; these profiles may be defined either analytically or by tabular input. The second option, for "bi-elliptic" geometries, requires the definition of profiles in the "lee" ($\phi = 0°$) and "wind" ($\phi = 180°$) planes, and optionally, the "side" plane, by tabular input.

The extension of this code to remove the pitch plane of symmetry includes the capability of defining geometric profiles (either analytically or by tabular input) for a range of ϕ from 0° to 360°. No modifications to the input variables have been made. However, if a fully asymmetric geometry is to be specified, profiles must be defined in both the $\phi = 0°$ and $\phi = 360°$ planes (which are identical).

SECTION 3

VALIDATION

The validation of the blunt body code modifications developed in this effort to remove the pitch plane of symmetry assumption has been carried out by comparisons of numerical results obtained with both the original and modified codes. This validation procedure is possible because the modifications required to remove the assumption of a pitch plane of symmetry have not altered the fundamental numerical algorithm, and the original blunt body code has been previously validated through extensive comparisons of numerical results to experimental data, as, for example, in Reference 4.

Because the basic numerical algorithm has not been altered, the modified blunt body code developed in this effort is subject to the same limitations on its applicability as the original code, except that flows without a pitch plane of symmetry can now be treated. These limitations have been investigated and discussed in Reference 4.

The first case examined in the validation of the modified blunt body code was the simple case of a sphere. Calculations were made with the original code at $\alpha = 5°$ (with a pitch plane of symmetry) and with the modified code at $\alpha = 0°$, $\beta = 5°$. Comparisons of the results, rotated to account for the change in wind vector, revealed no significant differences in the two calculations. As a further step in the validation process, afterbody solutions were computed using initial data from the two blunt body solutions, and, after the appropriate rotation of the results, no significant differences were found in the afterbody calculation in either the primary flow field parameters (e.g., pressure) or the integrated forces and moments.

Similar validation cases were run with nosetip geometries that were not axisymmetric, but which did have pitch planes of symmetry. (Calculations at sideslip with the modified code required the appropriate rotation of the nosetip geometry so that the plane of geometric symmetry would be aligned with the wind vector.) Again, after rotation of the results, it was found that the original and modified codes produced equivalent results.

SECTION 4

CONCLUSIONS

An existing inviscid blunt body code has been modified to remove the assumption of a pitch plane of symmetry, allowing calculations to be made at both angle of attack and sideslip for fully asymmetric nosetip geometries. All capabilities of the original code have been retained; both the original and modified codes are still subject to the following limitations on their applicability:

1.) The shock layer flow must be entirely inviscid, except for a thin boundary layer at the body surface.
2.) The nosetip shape must permit accurate flow field calculations using a spherical coordinate system.
3.) There can be no embedded shocks in the transonic flow field.

The modifications to the blunt body code have not increased the core storage requirements above those of the original code, and there has been no change in the computer time requirements (per grid point per iteration).

The code modifications described in this report are available in an UPDATE format for the SCOPE or NOS/BE1 operating systems. Qualified users may obtain these modifications through SAMSO (RSSE).

SECTION 5

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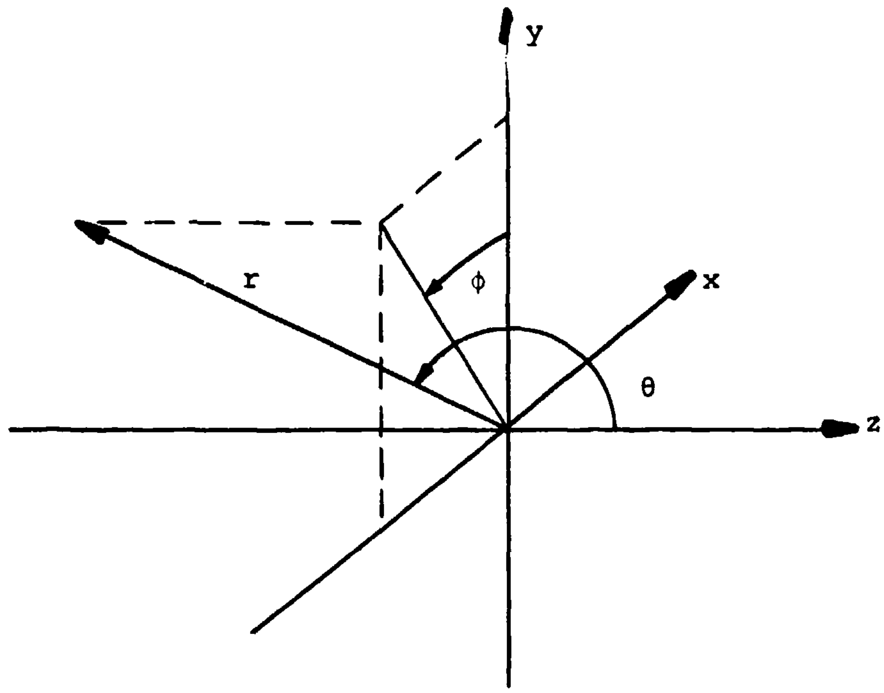

FIGURE 1. r,θ,z COORDINATE SYSTEM

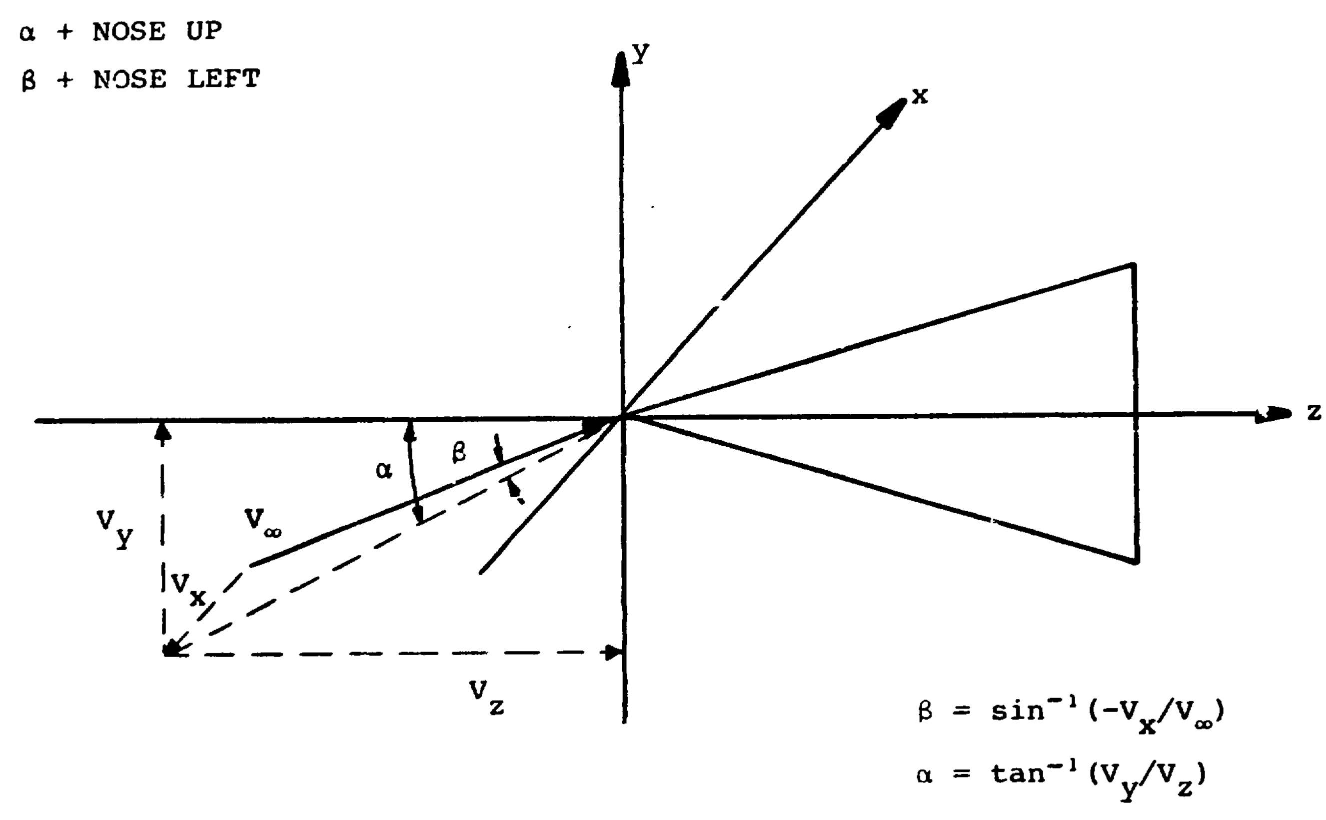

FIGURE 2. DEFINITION OF ANGLE OF ATTACK AND SIDESLIP ANGLE

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